SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 5359	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory 6b. OFFICE SYMBOL (If applicable) Code 6611	7a. NAME OF MONITORING ORGANIZATION
6c ADDRESS (City, State and ZIP Code) Washington, DC 20375	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research 8b OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c ADDRESS (City, State and ZIP Code) Arlington, VA 22217	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO.: 61153N-11 PROJECT NO.: RR011-08-43 TASK NO.: WORK UNIT NO.: DN780-023
11. TITLE (Include Security Classification) A Description and Discussion of Freddex Oceanographic Measurements	
12. PERSONAL AUTHOR(S) Bergin, J.M.	
13a. TYPE OF REPORT Interim 13b. TIME COVERED FROM TO	14. DATE OF REPORT (Yr., Mo., Day) July 19, 1984 15 PAGE COUNT 23
16. SUPPLEMENTARY NOTATION	

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Mesoscale variability Ocean eddies Underwater acoustics, sound speed anomalies Extension of sound speed profile

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

During the time interval March — June 1979 an experiment called FREDDEX (Front and Eddy Experiment) was conducted in the Atlantic Ocean, north of Bermuda, as a cooperative effort between several organizations and involved measurements made from satellite, aircraft, and three ships. The purpose of FREDDEX was to conduct extensive measurements on the oceanographic characteristics of an ocean eddy and the influence this feature has on long-range underwater acoustic transmission. This report discusses various salient aspects of the oceanographic measurements. Results are given for horizontal and vertical temperature structure of the eddy as well as evidence for the rotation of the basic temperature anomaly associated with the eddy. A novel technique is described of utilizing the ensemble of measurements in order to extend the data to the ocean bottom, thereby achieving a complete description of the sound speed profile in the vertical.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS ☐	21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL J. M. Bergin	22b TELEPHONE NUMBER (Include Area Code) (202) 767-2024 22c OFFICE SYMBOL Code 5110

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE

NRL Memorandum Report 5359

A Description and Discussion of Freddex Oceanographic Measurements

J. M. BERGIN

Acoustics Media Characterization Branch
Acoustics Division

July 19, 1984

NAVAL RESEARCH LABORATORY
Washington, D.C.

CONTENTS

A DESCRIPTION AND DISCUSSION OF FREDDEX OCEANOGRAPHIC MEASUREMENTS

INTRODUCTION

An exciting development in the field of oceanography is the fairly recent discovery that we must abandon the classical view of ocean circulation as comprising steady anticyclonic subtropical gyres in the major ocean basins above nearly quiescent deep water. Bretherton[1] has outlined how recent measurements show that the water circulates in a more complex manner and in fact that the flow must be regarded as turbulent. A significant component of the turbulent flow consists of fluctuations that occur in the so-called mesoscale range which involves time scales greater than a day and horizontal spatial scales from tens to hundreds of kilometers. Identifiable ocean structures in the mesoscale range include meanders of current systems such as the Gulf Stream, ocean rings shed by such current systems and mid-ocean eddies. A description of major experimental and theoretical attempts to understand the role of these mesoscale structures in ocean dynamics is given by Robinson[2] while much of the recent research efforts are summarized by McWilliams[3].

The existence of energetic motions in the mesoscale range has important implications for underwater acoustics. Since mesoscale currents are in approximate geostrophic balance, a mesoscale current structure will be associated with a perturbation of the main thermocline. This in turn implies that the sound speed structure will be perturbed from the structure one might expect on the basis of historical data. Consequently, mesoscale ocean structure implies the existence of sound speed anomalies in the mesoscale range. Such large-scale sound speed anomalies may have significant effects on long range acoustic propagation, while the mesoscale currents themselves may have important consequences for the mechanical behavior of long towed arrays.

A comprehensive field program named FREDDEX (for Front and Eddy Experiment) was carried out in 1979 to investigate the influence of mesoscale ocean structure on underwater acoustic array performance. The field program involved a detailed environmental and acoustic study of a cold-core Gulf Stream ring north of Bermuda. A description of the oceanographic research is given in this report. We note that from the point of view of underwater acoustics there seems little reason to make a distinction between rings and eddies. In our discussion we often refer to the ring as an ocean eddy, particularly when we are discussing properties of the ring which are common to ocean eddies. Primary objectives of the measurements were to (1) study the large scale eddy structure and its evolution over the course of the experiment, (2) determine the variability in the region surrounding the eddy, (3) determine the presence of surface fronts and spatial

Manuscript approved April 5, 1984.

variability in the mixed layer, (4) obtain data on the relationship of surface variability to satellite data, (5) study the relationship of surface variability to deeper ocean structure and (6) collect environmental data to support the related acoustics experiment.

The FREDDEX experiment represented a cooperative effort between several organizations and involved measurements by satellite, aircraft and three ships. The measurements are believed to represent the most extensive azimuthal sampling of the thermal structure of a Gulf Stream ring so far obtained. Moreover, three quasi-synoptic samples of the ring were obtained over the relatively short duration of about two weeks, thus providing a valuable data base for examining the temporal variability of the ring's structure. We report here on those aspects of the measurements which are essential to the acoustic studies. Those aspects of the research program which are primarily of oceanographic interest are either commented on briefly or reference is given to other publications where a more complete treatment may be found.

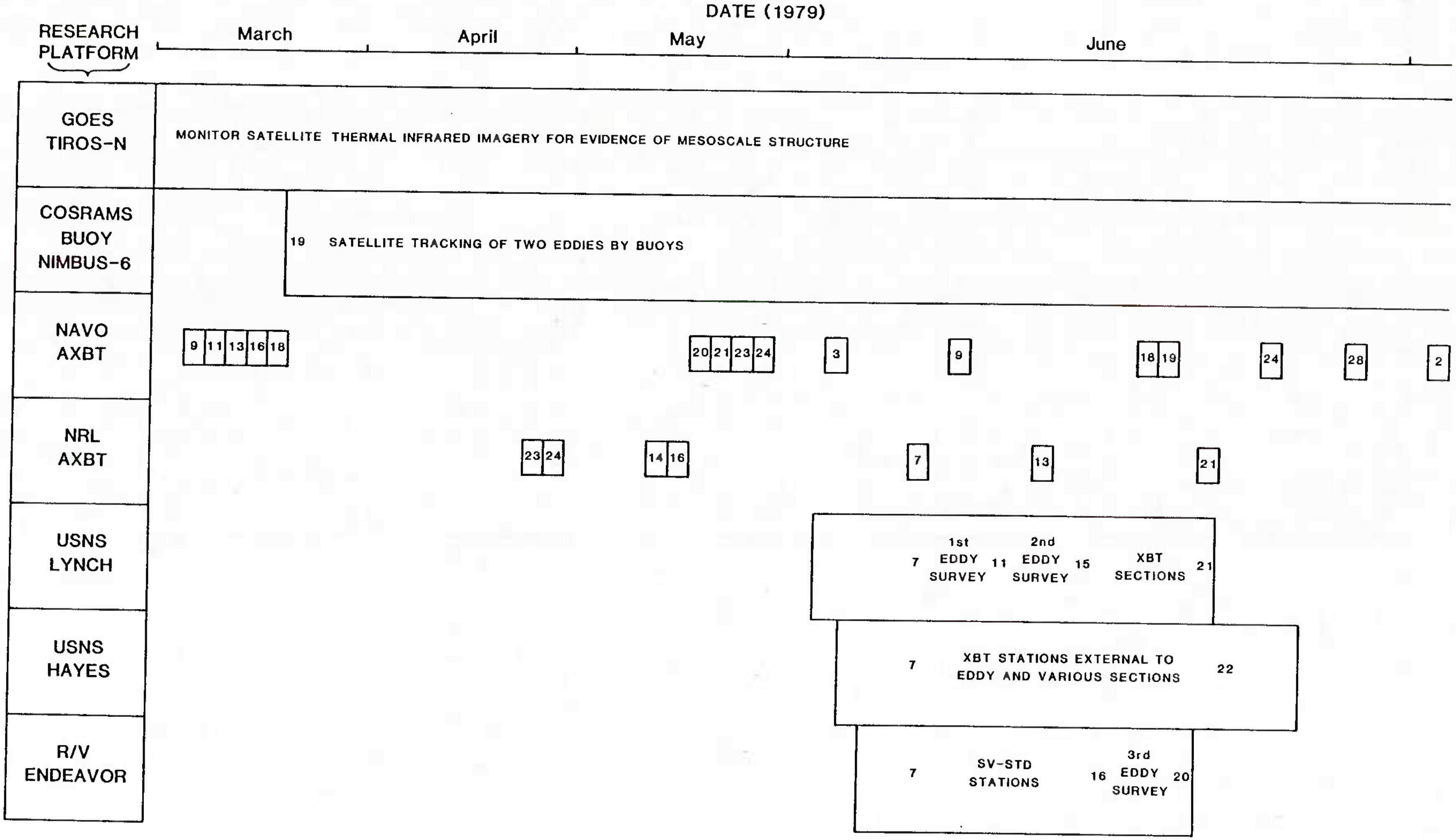
DESCRIPTION OF MEASUREMENTS

The overall objective of FREDDEX was to make detailed acoustic and oceanographic measurements of a cold-core Gulf Stream ring. A program of field measurements for an ocean eddy offers many difficulties. These difficulties arise because ocean eddies are essentially random events in the ocean, both in a spatial sense as well as in a temporal sense (i.e., their formation and movement are not predictable). Consequently, there were two main phases to the measurement program. The first phase involved an effort to locate and track candidate eddies, while the second phase involved a detailed study of the three-dimensional structure of the selected eddy.

A schematic illustration of the measurements performed during FREDDEX is given in Table 1. The localization of candidate Gulf Stream eddies was carried out in early March 1979 by an extensive series of airborne expendable bathythermograph (AXBT) measurements in the Sargasso Sea. Four eddies were discovered and the two most promising candidates for further study were "tagged" on 19 March by air-deployable buoys which were tracked via satellite and permitted real time tracking of the two eddies. A discussion of the characteristics of the buoys is given in Cheney et al.[4]. The strongest of the four eddies, and the one eventually selected for FREDDEX, was situated above Muir seamount, which was located 240km northeast of Bermuda.

Since the main phase of at-sea measurements was not to take place until June, it was necessary to monitor the general area of interest to ensure that (1) the two candidate eddies remained viable candidates and did not move from the area of planned operations, (2) no new eddy might form or migrate into the area and (3) the Gulf Stream did not migrate into a position that might unduly complicate acoustic measurements planned for June. Satellite infrared data from the GOES and TIROS-N satellites were examined from March through June in an effort to monitor mesoscale ocean structure in the northern Sargasso sea. Several AXBT flights were also made in order to verify the location of the primary eddy of interest and to make additional attempts at locating new eddies that might be present.

Table 1 Chart of research platforms utilized and oceanographic measurements performed during various time intervals of the FREDDEX experiment. Numbers designate dates. Note that the time scale for June is expanded relative to earlier months.



Shortly before the at-sea portion of the measurement program in June, a decision was made to select for further study the eddy which was first discovered northeast of Bermuda. The principal measurements of the eddy were carried out from three ships (USNS LYNCH, USNS HAYES, AND R/V ENDEAVOR) during a two-week period in June. However, satellite imagery continued to be monitored for a large-scale picture of the mesoscale structure in the area of interest and additional AXBT flights were made for a similar reason. The philosophy governing the ship measurements was that three rapid XBT surveys of the detailed azimuthal eddy thermal structure should be carried out in order to have a good basis for determining any changes that might occur in the spatial structure of the eddy over the two-week period. Such repetitive sampling is in contrast to most oceanographic measurements of eddies which involve a single determination of eddy structure, usually along one or two cuts through the eddy. Our detailed azimuthal sampling, which involved as many as ten radial cuts through the eddy, was necessitated by the fact that acoustic signals were transmitted at various angles through the eddy to a receiver array positioned at various locations over the two week period.

The thermal structure of the eddy was determined by the use of T5 and T7 XBT probes. The T7 probes reached a depth of approximately 800m while the T5 probes reached approximately 1600m. Our use of T5 probes was motivated by the desire to acquire measurements to depths greater than the level at which the sound speed attains its minimum. This implies that any extrapolation to construct sound speed structure to the bottom will be over a range in which the sound speed has a relatively simple behavior (e.g., increasing approximately linearly with depth). Our deep measurements seem highly desirable as compared to sampling schemes which utilize measurements to much shallower depths and then attempt to infer the nature of sound speed variation near its minimum and below. The spatial sampling rate varied from about every 10km for the LYNCH and ENDEAVOR to 20km for the HAYES.

An important set of measurements supplementary to the XBT measurements consisted of 28 SV-STD stations made by the ENDEAVOR in the vicinity of the eddy as well as along a diameter through the eddy. These stations were carried out to a depth of 3000m except for 3 stations down to the bottom. These measurements provided data on the deep thermal structure of the eddy as well as on the salinity structure.

An interpretation of the most significant aspects of the data that have a bearing on the underwater acoustics experiment is given in the following sections. Most of the discussion will deal with the measurements made from the three ships since these are the critical ones that reveal the eddy structure. The AXBT data will receive little further comment since it was aimed at monitoring the presence of various features rather than their detailed structure. Additional information about the AXBT data is available in Feden and Bergin[5], Barrett et al.[6], and Petrick et al.[7]. Further details concerning the measurements carried out during FREDDEX appear in FREDDEX Report #1[8,9].

MOVEMENT AND EVOLUTION OF THE FREDDEX EDDY

An example of the dynamic behavior of ocean eddies is provided by the trajectory of the center of the FREDDEX eddy which is displayed in Fig. 1 for the time interval from 19 March through 4 July. Estimates of the eddy center were obtained from a study of the orbits of the COSRAMS buoy around the center. The motion of the center initially consisted of a looping trajectory in the form of a figure eight over a distance of some 180km followed by a somewhat erratic movement to the northwest. An average translation speed of almost 2km/d is indicated for the three month period, although much higher translational speeds may apply for shorter time intervals. The general pattern of behavior exhibited by the path of the FREDDEX eddy is consistent with the behavior observed for similar ocean eddies[10,11,12]. It should be mentioned that there does not exist, at present, any acceptable theoretical framework for predicting the trajectory of such an eddy. An important practical aspect of planning measurements on such a dynamic feature is the very real necessity of fairly continuous tracking, since a ship operation of the type we carried out will usually occur long after the feature is first discovered.

An interesting aspect of the detailed ship measurements was evidence that the shape of the eddy was changing as a function of time. The ship measurements were carried out over a two week period beginning on 7 June and consisted of three surveys of the eddy in the general form of a pinwheel pattern around the center of the eddy. Contours of the temperature field at a depth of 400m are shown in Fig. 2 for each of the three surveys. The temperature varies from about 10°C at the eddy center to a fairly uniform value of about 18°C outside the eddy, which is consistent with the presence of the 18°C thermostad in the Sargasso Sea thermal structure[13]. Lateral dimensions of the eddy, based on the 17°C isotherm at 400m, vary from 222km x 167km for the first eddy survey to 296km x 139km for the third eddy survey. An average diameter for the three eddy surveys is approximately 200km for the 17°C isotherm at 400m. This dimension compares favorably with other estimates of cyclonic Gulf Stream ring diameters when allowance is made for the fact that our estimate applies to a deeper level (400m) than the 250m level used in other discussions[14,15]. The important feature of the three eddy shapes is the departure from a circular shape, which becomes most exaggerated in the third shape estimate. The departures from a circular shape seem to suggest the existence of perturbations to a circular structure which propagate in a cyclonic, or counterclockwise, direction around the eddy.

These perturbations have been interpreted as indicating the existence of a wavelike component to the structure of the eddy which appears to propagate around the circumference of the eddy at approximately 10°/day[16]. A detailed analysis of the evolution of the eddy was carried out by Mied et al.[17] They examined in detail the departure from a circular structure and found that the disturbance was predominantly an azimuthal mode of second order. Moreover, analysis of the energetics of the disturbance growth was estimated as 16 days while the time scale for energy loss from the disturbance is about 4.5 days. This seems to offer an explanation of observations which indicate that the rate of rotation of azimuthal structures can vary with time.

Additional observations which indicate that eddies may have an azimuthal structure were reported by Olson and Spence[18]. A more detailed study of the eddy discussed by Olson and Spence was carried out by Spence and Legeckis[19], who utilized satellite thermal infrared imagery. They found that the eddy appeared to be a cyclonically rotating oval and carried out a stability analysis.

The realization that eddies may have a wavelike component to their structure is a relatively recent development. Our present understanding of such structure must be regarded as rather tentative. However, it should be noted that azimuthal structure may have a profound influence on the speed and translation of the eddy[20]. The potential role of azimuthal structure in the evolutionary process of an eddy would also appear significant for understanding the life cycle of eddies.

The evolution of the eddy into the structure exhibited in Fig. 2(c) may have been influenced by the formation of a new Gulf Stream ring northeast of the FREDDEX eddy. Evidence of the formation of the new ring can be seen in Fig. 3 which is a TIROS-N satellite thermal infrared image for 15 June. The approximately circular structure near the center of the image indicates the presence of a Gulf Stream ring which developed from a southward meander of the Gulf Stream beginning near the end of May much farther to the north. The distance between the center of the new ring and the FREDDEX eddy was approximately 320km on 15 June. This separation seems large enough in comparison to the dimensions of the two features to rule out any strong or direct interaction between the two eddies. However, our data are not conclusive on this point. The satellite image in Fig. 3 does indicate, though, the rather dramatic changes which can occur in the vicinity of the Gulf Stream. Additional details about the new ring are given by Blumenthal and Gotthardt[21].

SOUND SPEED STRUCTURE FOR THE ACOUSTIC STUDIES

A major aspect of FREDDEX was the performance of acoustic transmission measurements through the eddy during the time frame of 16 - 21 June. A central ingredient for that analysis is the variable sound speed structure associated with the eddy structure. We therefore make additional comments about the oceanographic data and the eddy structure from the point of view of the needs for the acoustic analysis.

For the time frame indicated, measurements carried out during the third survey of the eddy are of primary importance. The horizontal structure of the eddy revealed by the third eddy survey was discussed above in connection with Fig. 2(c). Equally significant for sound speed structure is the change in vertical temperature structure produced by the eddy. Some examples of the vertical temperature structure are given in Fig. 4. Figure 4(a) shows the temperature structure as a function of depth and distance along a straight track made to the west of the eddy and outside the direct influence of the eddy. The temperature structure therefore indicates the "undisturbed" Sargasso Sea condition. A mixed layer is present which extends from the surface down to about 50m at which depth a seasonal thermocline occurs. Temperatures in the seasonal thermocline vary from about 24°C down to 19°C near the base of the seasonal thermocline which lies at a nominal depth of 200m. Extending from 200m to 600m is a layer of water in which the temperature only varies from 17°C to 19°C. This fairly homogeneous water is a permanent characteristic of the Sargasso Sea.[13] The main thermocline extends from about 600m down to about 1200m. A temperature change of some 10°C takes place over this 600m depth interval and accounts for a significant portion of the deep sound channel.

Figure 4(b) shows the vertical temperature structure in the eddy along an east-west section through the eddy center. Several dramatic changes in structure are apparent. The seasonal thermocline and the fairly homogeneous layer below it are much thinner at the eddy center as compared to conditions outside the eddy. The main thermocline shows no appreciable thinning but instead is displaced upward by some 400m at the eddy center. Individual isotherms in the main thermocline or slightly below it may be displaced by even larger amounts.

The magnitude of the vertical excursion of isotherms in the main thermocline is a useful parameter to characterize the strength of eddies. For example, Parker[14] in a study of historical data found certain correspondences between various ring parameters and the height of the 17°C isotherm above the 500 depth level, which he calls the 'height of the anomaly'. One correlation of interest is the comparison between ring diameter at a depth of 250m (based on the 17°C isotherm) and the anomaly height. Our data gives a ring diameter of 48 n.miles and an anomaly height of 350m. From Parker's study the expected range of anomaly heights for our ring diameter is from 250m to 460m. The FREDDEX ring is therefore representative of the midpoint of this range of anomaly heights. Our anomaly height is also at the midpoint of the spread in values associated with the latitude of the FREDDEX ring (see Parker's Fig. 6b).

Another aspect of vertical structure that has been examined by previous investigators is the rate of subsidence of isotherms in the main thermocline. The ship and aircraft data over the four month observation period of FREDDEX indicates that isotherms in the main thermocline subsided at a rate of 1.7 to 1.8 m/d. This is larger than average values of .6m/d[10,12,14] and .8 m/d [10,12,14] found for other rings but Fuglister's data[10] shows an increased rate, comparable to our estimate, over an interval of two months. The rate of subsidence is undoubtedly influenced by interactions the ring may experience during its lifetime. Consequently, some variability in values for this parameter are to be expected.

Sound speed C is generally expressed in terms of its dependence on oceanographic parameters as a relation of the form $C = C(T,S,p)$ where T designates temperature, S salinity, and p the pressure (which is closely related to the depth). The importance of the changes in vertical temperature structure associated with the eddy is that they strongly alter the vertical and horizontal sound speed structure through the dependence of sound speed on temperature. However, salinity also plays a role in determining sound speed, although its influence is generally much weaker than that of temperature. Salinity changes associated with the eddy are best studied by use of a T-S diagram. Figure 5 shows two T-S relations based on the STD data taken by the R/V ENDEAVOR. One of the T-S correlations is for data taken at the center of the eddy while the second correlation is for a data station well outside the influence of the eddy. The two stations were selected to demonstrate the maximum difference that might arise in T-S behavior. For the FREDDEX eddy the salinity anomaly is of the order 0.12 ppt at most. Consequently, we can to good approximation assume that a unique T-S relation applies to the FREDDEX eddy and its exterior. This allows us to determine salinity for the sound speed calculation from temperature and a representative T-S relation for the region.[22] We note that a comparison of the T-S data for the exterior station with the mean T-S structure for the Sargasso Sea as given by Iselin[23] indicates that the station data outside the eddy is representative of the mean conditions, at least for temperatures cooler than 20°C. The layer of water with temperatures greater than 20°C may show a rather erratic departure from the mean T-S structure because this layer is directly influenced by atmospheric processes.

The deviations in T-S structure of the central station from the exterior station give some indication as to the origin of the eddy and its age. The main differences between the curves in Fig. 5 occur for temperatures warmer than 18°C or, equivalently, for depths shallower than about 300m. The water between 18°C and 22°C in the eddy center shows a distinctly less saline structure compared to the Sargasso Sea structure. The magnitude of the salinity anomaly for this layer is 0.12 ppt and indicates that this water originated from a water mass other than the Sargasso Sea, namely the slope water north of the Gulf Stream. We conclude that the FREDDEX eddy originated from a meander of the Gulf Stream that pinched off to form a cold-core ring.

It is somewhat more difficult to comment on the age of the FREDDEX eddy. However, it is known that new rings at formation have salinity anomalies on the order of 1 ppt or larger.[10,24] Richardson et al.[25] have documented a salinity anomaly of 0.35 ppt, which extended down to about 400 to 500m in depth, for a Gulf Stream ring 2.5 months after formation while McCartney et al.[15] have found salinity anomalies of 0.15 ppt for Gulf Stream rings whose age was estimated at about 11 months. Since we expect the salinity anomaly to decay according to a smooth rule of behavior, the above observations indicate an age greater than 2.5 months but less than 11 months, with the probable age being much closer to 11 months than the younger age limit. We, of course, know that in June 1979 the FREDDEX eddy was at least 3 months old since it was discovered in March 1979 as a feature well separated from the Gulf Stream.

A related aspect is the surface temperature anomaly between the core of the ring and its exterior which also arises as a consequence of the water mass in the core having a different origin than the exterior water. Gulf Stream rings are often visible in satellite infrared imagery when they are first formed and possess a strong surface temperature anomaly. The FREDDEX ring, however, had a relatively weak temperature anomaly of 2.6 - 2.8°C at the surface when it was first detected in mid-March by AXBT measurements. This temperature contrast lies near the midpoint of the range expected for the latitude of the FREDDEX ring according to the results compiled by Parker[14]. AXBT measurements in April and May indicated that the magnitude of the surface temperature anomaly remained approximately constant over a two month period but, by mid-June, the surface temperature contrast had virtually disappeared as a result of seasonal heating of the near surface layers. The measurements in June revealed that temperatures in the center of the ring averaged about 24°C while outside the ring the average was about 24.5°C. This provides a surface thermal contrast of only 0.5°C. Although summer heating can have a strong effect on a ring's surface temperature anomaly, Fuglister[10] described ring data which indicates that a surface temperature anomaly can persist at a level of 1-2°C over a 5-month period.

Long range acoustic propagation through an ocean eddy is influenced by the entire sound speed structure of the eddy, from ocean surface to ocean bottom, and it is now necessary to explain how this sound speed structure is determined from our measurements which are, for the most part, limited in depth. We earlier indicated that the spatial sampling seems to give adequate resolution of the large-scale structure of the eddy. We have also shown that salinity may be adequately determined from temperature by the use of a mean T-S relation. The real question is the downward extension to the ocean bottom of the XBT data. This problem may be further made precise by recalling that for the acoustic studies carried out in this report the time frame of interest is from 16 - 21 June during which the detailed eddy survey was carried out using the relatively shallow T7 probes (limited to depths slightly greater than 800m). We employed a novel extension method that may be of use in other investigations of mesoscale features.

The main principle we used in extending the data is based on the fact that the temperature perturbation associated with the eddy tends to die out with depth below, for example, the 800m level which is deep enough not to be strongly influenced by near-surface processes. Consequently, if two XBT samples are taken from the same eddy which are close in temperature at the 800m level then we would expect the two samples to remain in close agreement at all greater depths. Note that there is no requirement that the samples be located near each other in space or in time. There is a requirement that the samples apply to the same eddy and be taken over a time interval that is small compared to the lifetime of the eddy. This implies that we may use all the XBT and STD data taken during the FREDDEX operation to achieve a downward extension of the T7 data.

The actual means by which the extension is carried out is outlined in Fig. 6 according to the nature of the data and the depth interval involved. The FREDDEX data consists, in a collective sense, of four types of data: XBT-T7 data which apply down to slightly more than 800m, XBT-T5 data which are good down to somewhat more than 1500m, shallow STD casts which terminate at about 3000m, and three deep STD casts which reach at least 4300m. T7 data are first extended down to 1500m by segregating the T5 data into groups which each span a temperature interval of 0.5°C at the 800m level. Each T7 data station is then matched to an appropriate group on the basis of its temperature at 800m; the T7 data is extended to 1500m by using the average of the T5 data in the group. An extension of this data is then carried out to the 2900m level by following a similar procedure. Shallow

STD casts are segregated in groups each of which span a temperature interval of 0.1°C at the 1500m level. Each T7 data station (which was extended to 1500m by the first step) is now matched to an appropriate group of the shallow STD casts and an extension is made to 2900m using the average of the STD casts in the group. For the depth interval between 2900m and 4300m, the extension is carried out using the average of the 3 deep STD stations. Below 4300m, each data station can be extended in the sound speed domain on the basis of a constant sound speed gradient. This extension scheme, although it appears rather complicated, has the advantage that it is based on actual measurements made in the eddy.

Some examples of sound speed profiles generated by this technique are shown in Fig. 7. They were selected to also demonstrate the large changes in sound speed structure produced by the eddy. The profile labeled "external condition" represents the sound speed variation with depth in the "undisturbed" Sargasso Sea outside the main influence of the eddy. The two profiles labeled 'eddy center region' apply to the center of the eddy where the maximum perturbation of sound speed structure occurs. The two profiles for the center region are for a T5 and T7 probe and agree fairly well. The small differences between the two center stations seem accountable in terms of their spatial separation of 40 km; an implication of these small differences is that the eddy center region, or the region of maximum deviation from the normal state, is fairly extensive in a spatial sense.

The major difference in sound speed structure between the eddy center and its surroundings are easily seen in the figure. The deep sound speed minimum occurs at a depth of about 950m in the eddy center while outside the eddy its depth is about 1400m. Furthermore, the magnitude of the sound speed at its deep minimum is less by 6 m/s for the eddy center; this reduction seems mainly associated with the pressure influence on sound speed. The total horizontal gradient in sound speed between eddy center and exterior is more or less confined to the upper water column, above the 1400m level, where the main thermocline occurs. The maximum horizontal difference in sound speed is 30 m/s in the depth range of 600 - 700m, but a rapid reduction of this difference takes place as we move away from that depth level.

Implications of a sound speed anomaly of this magnitude on array performance are dealt with elsewhere. It should be emphasized that the changes in sound speed structure associated with the FREDDEX eddy are not uncommon but are, in fact, fairly typical of the changes one might expect for cold eddies produced by the Gulf Stream.[12,26,27] A discussion of comparable changes in sound speed structure associated with a warm Gulf Stream eddy (located north of the Stream) has recently been given by Fenner[28].

SUMMARY AND CONCLUDING REMARKS

Our discussion has been primarily concerned with a cyclonic Gulf Stream ring that was intensively studied during the FREDDEX experiment of March-June 1979. Although the oceanographic measurements do have a direct bearing on many aspects of Gulf Stream ring behavior of current importance to basic oceanographic research, we have primarily discussed the measurements from the point of view of underwater acoustics. We briefly commented on certain oceanographic aspects such as ring movement and evolution. Of most concern, however, was the horizontal and spatial structure of the sound speed anomaly associated with the thermal structure of the Gulf Stream ring and the method by which the complete sound speed structure is derived from measurements that do not span the entire depth of the water column.

The overall characteristics of the FREDDEX ring were found to be fairly typical of cyclonic Gulf Stream rings which are still in an early stage of their life cycle with strong anomalies in temperature and sound speed.

Any assessment of the acoustic significance of Gulf Stream rings must take into account their probable distribution in the ocean. Estimates of the formation rate of Gulf Stream rings indicate that 5-8 rings may form on each side of the stream per year[29]. The mean lifetime for cyclonic rings is believed to range from 1 - 1.5 years with a maximum of perhaps 3 years[12]. This indicates that at any given time there may be from 5-12 cyclonic rings in the Sargasso Sea. Synoptic studies of the Gulf Stream ring population have tended to confirm this population estimate.[30,31] The cyclonic rings may occupy 10 percent of the total area of the Sargasso Sea but, when their tendency to occur in the northern and western areas of the Sargasso Sea is accounted for, the cyclonic rings may occupy 30 percent of region they tend to appear in. These estimates point out that cyclonic rings are sufficiently numerous to require evaluation in terms of the impact they may have on underwater acoustics.

Anticyclonic, or warm core, rings form north of the Gulf Stream at the same rate as the cyclonic rings. Their mean lifetime appears to be 0.5 year with 3-4 warm core rings existing at any given moment.[30] Although less numerous than their cold core counterparts, the warm rings occur in a much more limited region of the ocean where the additional complication of interaction with the continental slope must be considered in their dynamical evolution.

Gulf Stream rings are now known to be particular examples of a general class of ocean variability usually referred to as ocean eddies. As a consequence of experiments such as POLYGON, MODE, and POLYMODE, ocean eddies were found to be a dominant and general component of ocean variability which may be present in any part of the world ocean.[32,33] The special nature of Gulf Stream rings arises because their source and formation process are known; the rings also appear to be among the most intense members of the ocean eddy population in terms of their vertical perturbation of the main thermocline and their associated current speeds. Ocean eddies that are some distance from strong currents, such as the Gulf Stream, do not have an unambiguous source mechanism. Several possible mechanisms have been cited such as the radiation of waves from rings, the action of surface winds, flow over bottom topography, instabilities of large scale flows, or as a consequence of the interaction of two eddies. It seems that ocean eddies are best regarded as constituting a spectrum of disturbances in the ocean which play a significant but not fully understood role in the dynamics of the ocean circulation.

The presence of such an energetic spectrum of eddy disturbances in the ocean demands an evaluation of its signficance in terms of the various concerns of underwater acoustics. We have addressed this problem by a careful oceanographic study of a Gulf Stream ring which typifies the stronger ocean eddies. A thorough discussion of the long-range acoustic transmission through the ring discussed here will be found in ref. 34.

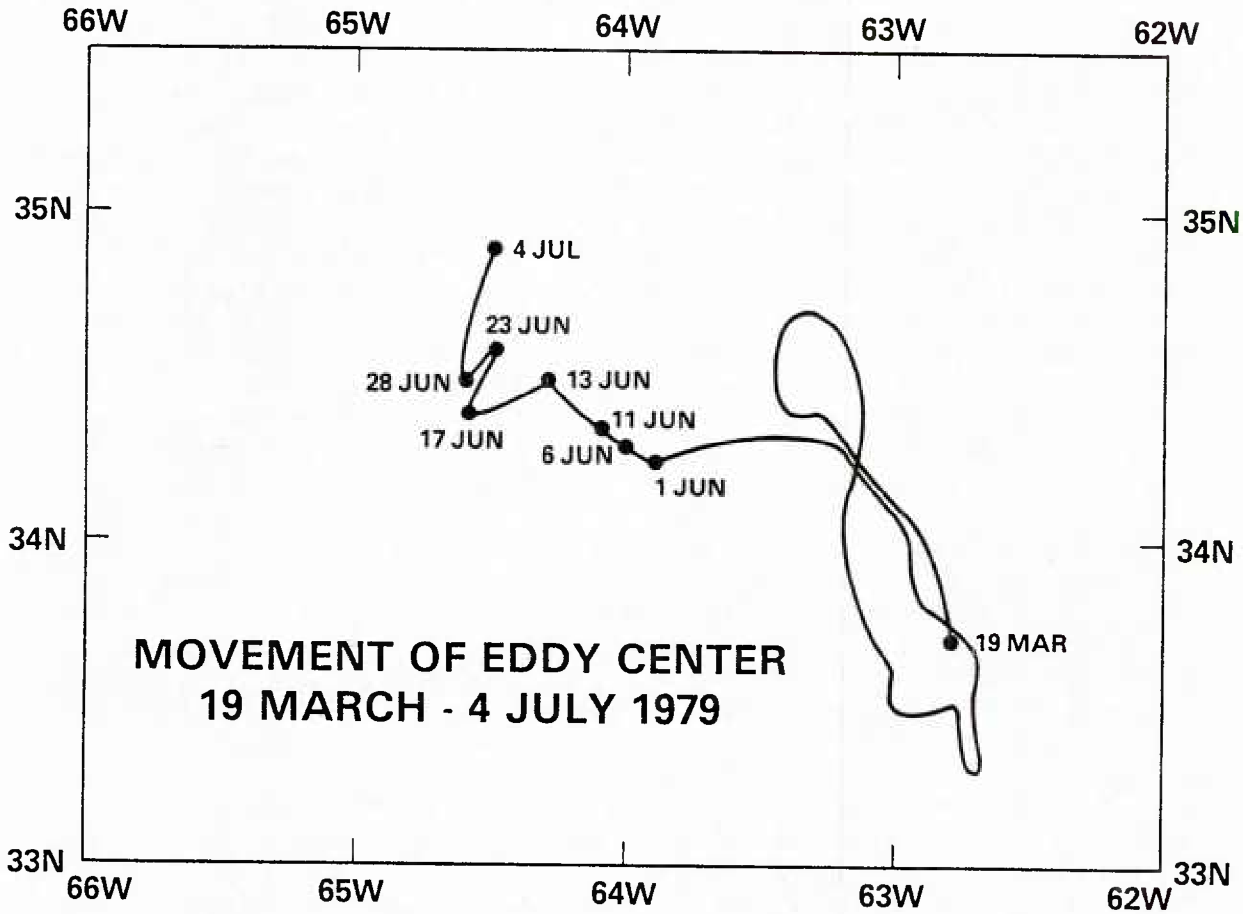
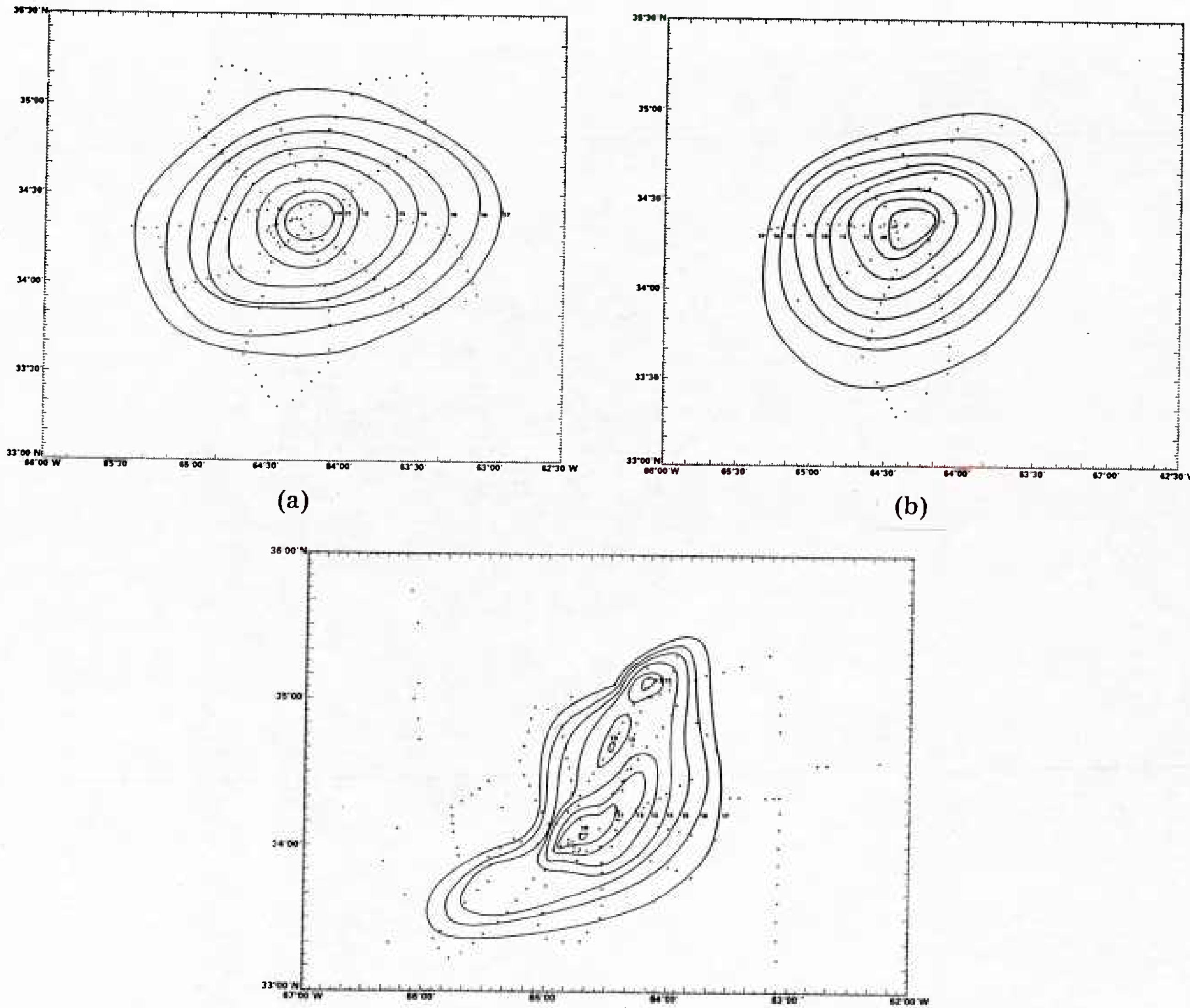


Figure 1 Path of the FREDDEX ring as estimated by satellite tracking of a drifting buoy implanted in the ring's center on March 19.



(a) (b)

(c)

Figure 2 Changes in the shape of the eddy over a two week period from 7 - 21 June 1979. XBT locations are indicated by dots. Contours of the temperature field at 400m for (a) the time interval 7 - 11 June, (b) the time interval 11 - 15 June, and (c) the time interval 16 - 21 June.

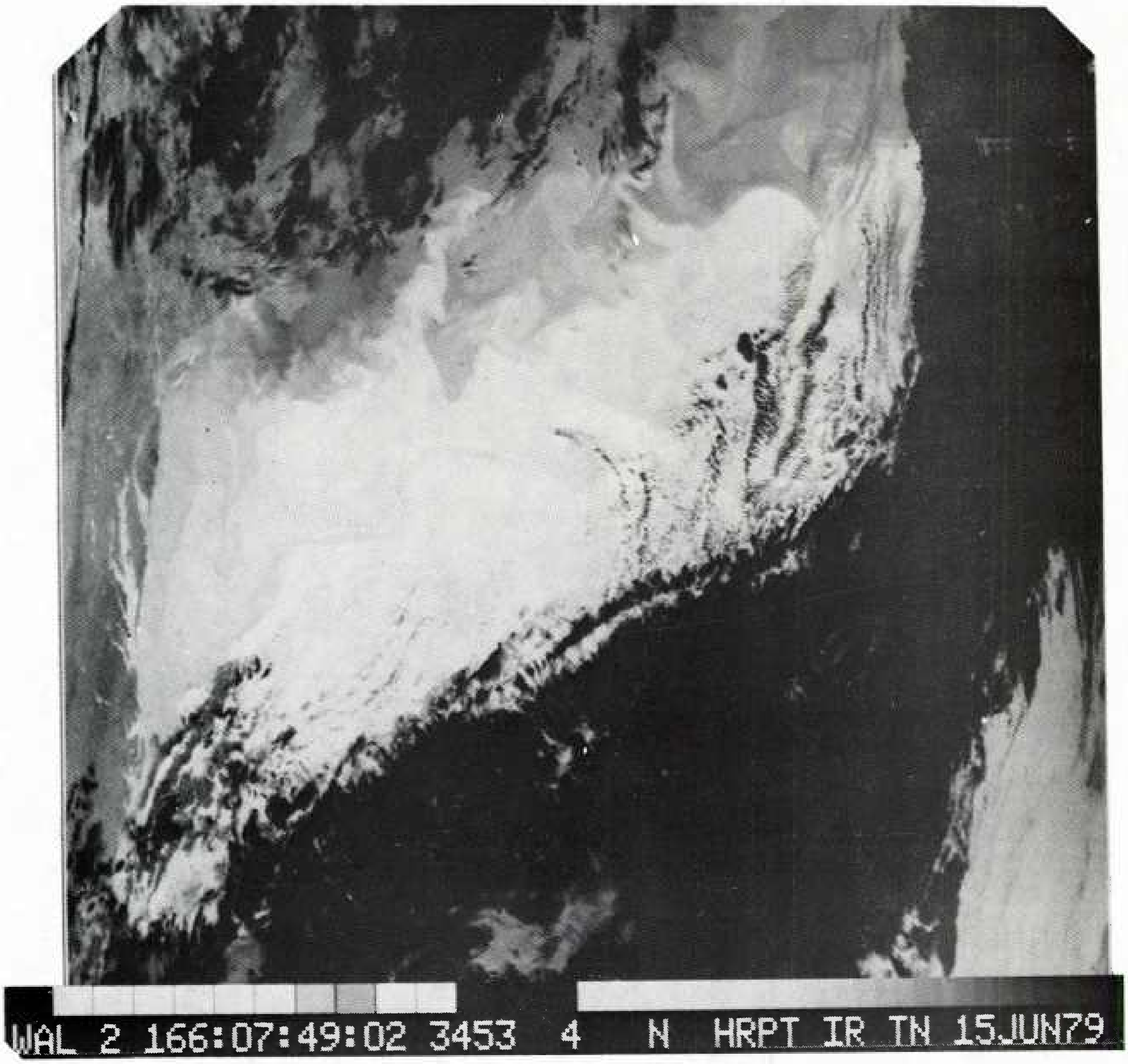
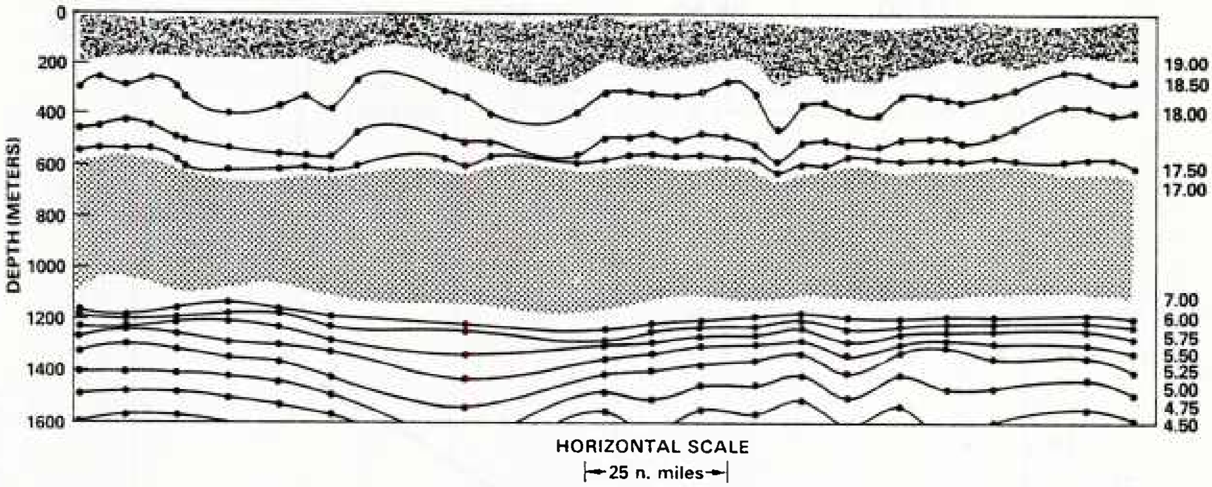
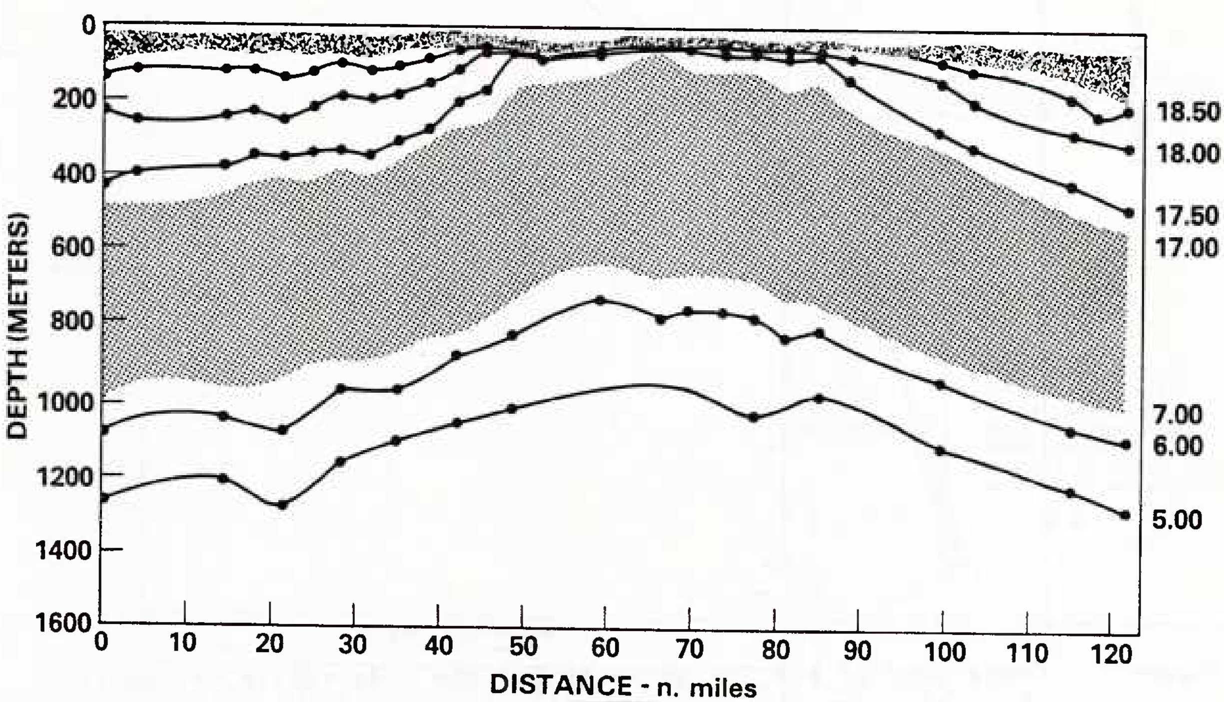


Figure 3 TIROS-N satellite infrared imagery for 15 June indicating the Gulf Stream and a new Gulf Stream ring apparently still attached to the stream. The FREDDEX ring is located to the south of the new ring and is obscured by cloud cover.



(a)



(b)

Figure 4 Effect of the FREDDEX eddy on the ocean thermal structure. The thermal structure in the 'undisturbed' Sargasso Sea outside the direct influence of the eddy is shown in (a) while the thermal structure associated with the eddy appears in (b). The shaded portion near the ocean surface represents the seasonal thermocline, above which lies the surface mixed layer. The dotted region represents the main thermocline.

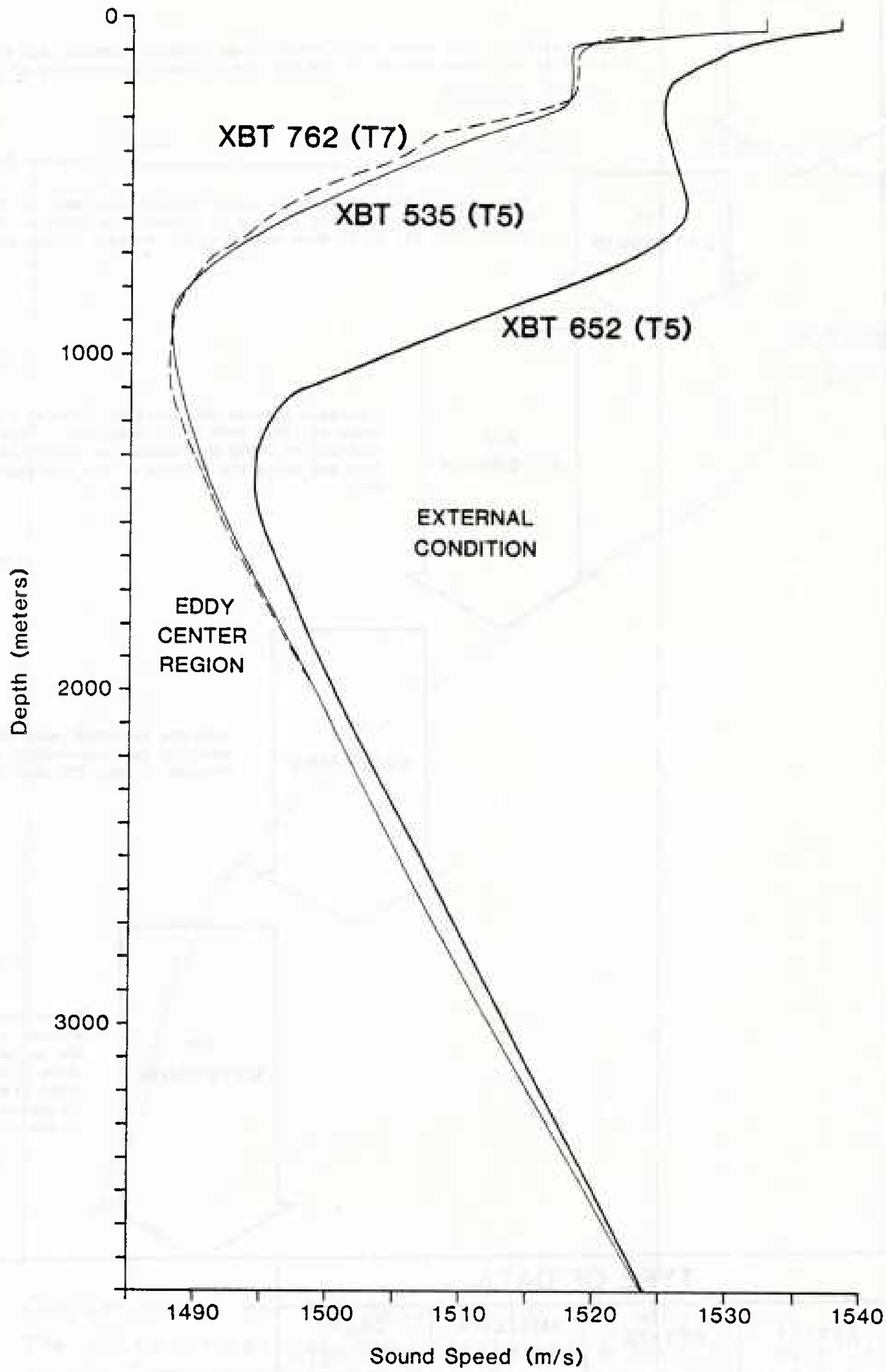


Figure 7 Sound speed profiles obtained by the method of extension outlined in the text for the eddy center and the undisturbed exterior region. The two profiles for the eddy center region are from a T7 and a T5 probe. Minor differences between the two profiles for the center region can be accounted for in terms of their large spatial separation of 40km, while the absence of any major difference demonstrates the utility of the method of extension.

REFERENCES

1. F. P. Bretherton, "Recent developments in dynamical oceanography," Quart. J. Roy. Met. Soc. 101, 705-721 (1975).

2. A. R. Robinson, "Eddies and ocean circulation," Oceanus 19, 2-17 (1976).

3. J. C. McWilliams, "A review of research on mesoscale ocean currents," Rev. Geophys. and Sp. Phys. 17, 1548-1558 (1979).

4. R. E. Cheney, P. L. Richardson, and B. P. Blumenthal, "Air deployment of satellite-tracked drifters," J. Geophys. Res. 85, 2773-2778 (1980).

5. R. H. Feden and J. M. Bergin, "AXBT measurements of a Gulf Stream ring above Muir seamount," EOS, Trans. Am. Geophys. Union 17, 260-261 (1980).

6. R. L. Barrett, G. A. Gotthardt and K. Petrick, "Airborne environmental survey in the western North Atlantic during Fox-II, June - July 1979," U. S. Naval Oceanogr. Office Tech. Note TN-3440-6-79 (1979).

7. K. Petrick, R. L. Barrett and G. A. Gotthardt, "Airborne oceanographic data collected from 3 June to 2 July 1979 in support of Fox II," U. S. Naval Oceanogr. Office Tech. Note TN-3440-7-79 (1979).

8. FREDDEX Report #1, "Summary of FREDDEX developments prior to at-sea phase," available from Code 5160, Naval Research Laboratory (1979).

9. Further information is available from Code 5160, Naval Research Laboratory, Washington, DC.

10. F. C. Fuglister, "A cyclonic ring formed by the Gulf Stream, 1967," In A Voyage of Discovery, George Deacon 70th Anniversary Volume, M. V. Angel, Ed. (Pergamon, New York 1977), pp. 177 - 198.

11. P. L. Richardson, "Gulf Stream ring trajectories," J. Phys. Oceanogr. 10, 90-104 (1980).

12. The Ring Group, "Gulf Stream cold-core rings: their physics, chemistry, and biology," Science 212, 1091-1100 (1981).

13. L. V. Worthington, "The 18° water in the Sargasso Sea," Deep-Sea Res. 5, 297-305 (1959).

14. C. E. Parker, "Gulf Stream rings in the Sargasso Sea," Deep-Sea Res. 18, 981-993 (1971).

15. M. S. McCartney, L. V. Worthington, and W. J. Schmitz, Jr., "Large cyclonic rings from the northeast Sargasso Sea," J. Geophys. Res. 83, 901-914 (1978).

16. J. M. Bergin, "Gulf Stream ring structure and evolution over a short time interval," Eos. Trans. Am. Geophys. Union 61, 261 (1980).

17. R. P. Mied, G. J. Lindemann, and J. M. Bergin, "Azimuthal structure of a cyclonic Gulf Stream ring," J. Geophys. Res. 88, 2530-2546 (1983).

18. D. B. Olson and T. W. Spence, "Asymmetric disturbances in the frontal zone of a Gulf Stream ring," J. Geophys. Res. 83, 4691-4695 (1978).

19. T. W. Spence and R. Legeckis, "Satellite and hydrographic observations of low-frequency wave motions associated with a cold-core Gulf Stream ring," J. Geophys. Res. 86, 1945-1953 (1981).

20. G. R. Flierl, "The application of linear quasi-geostrophic dynamics to Gulf Stream rings," J. Phys. Oceanogr. 7, 365-379 (1977).

21. B. P. Blumenthal and G. A. Gotthardt, "Formative stages of a Gulf Stream cyclonic ring," Gulfstream 5, 3-7 (1979).

22. W. J. Emery, T. J. Reid, J. A. DeSanto, R. N. Baer and J. P. Dugan, "Mesoscale variations in the deep sound channel and effects on low-frequency sound propagation," J. Acoust. Soc. Am. 66, 831-841 (1979).

23. C. O. Iselin, "A study of the circulation of the western North Atlantic," Pap. Phys. Oceanogr., Meterol., 4, 101 pp. (1936).

24. P. L. Richardson, R. E. Cheney and L. A. Mantini, "Tracking a Gulf Stream ring with a free drifting surface buoy," J. Phys. Oceanogr. 7, 580-590 (1977).

25. P. L. Richardson, C. Maillard and T. B. Stanford, "The physical structure and life history of cyclonic Gulf Stream ring Allen," J. Geophys. Res. 84, 7727-7741 (1979).

26. A. C. Vastano and G. E. Owens, "On the acoustic characteristics of a Gulf Stream cyclonic ring," J. Phys. Oceanogr. 3, 470-478 (1973).

27. D. E. Hagan, D. B. Olson, J. E. Schmitz and A. C. Vastano, "A comparison of cyclonic ring structures in the Northern Sargasso Sea," J. Phys. Oceanogr. 8, 997-1008 (1978).

28. D. F. Fenner, "Sound speed structure across an anticyclonic eddy and the Gulf Stream North Wall," J. Geophys. Res. 83, 4599-4605 (1978).

29. F. C. Fuglister, "Cyclonic rings formed by the Gulf Stream, 1965-1966," in Studies in Physical Oceanography, vol. 1, A. Gordon, Ed. (Gordon and Breach, New York, 1972), pp. 137-167.

30. D. Y. Lai and P. L. Richardson, "Distribution and movement of Gulf Stream rings," J. Phys. Oceanog. 7, 670-683 (1977).

31. P. L. Richardson, R. E. Cheney, and L. V. Worthington, "A census of Gulf Stream rings, Spring 1975," J. Geophys. Res. 83, 6136-6144 (1978).

32. Mode Group, "The mid-ocean dynamics experiment," Deep-Sea Res. 25, 859-910 (1978).

33. M. N. Koshlyakov and A. S. Monin, "Synoptic eddies in the ocean," Ann. Rev. Earth Planet. Sci. 6, 495-523 (1978).

34. K. M. Guthrie, D. R. DelBalzo, D. M. Dundore, L. J. Rosenblum, J. M. Bergin, and B. B. Adams, "The effect of a Gulf Stream ring on towed array performance," to appear in J. Underwater Acoustics (1983).

DEPARTMENT OF THE NAVY

NAVAL RESEARCH LABORATORY
Washington, D.C. 20375

OFFICIAL BUSINESS

PENALTY FOR PRIVATE USE, $300

POSTAGE AND FEES PAID
DEPARTMENT OF THE NAVY
DoD-316

THIRD CLASS MAIL

SUPERINTENDENT
NAVAL POSTGRADUATE SCHOOL
ATTN: TECHNICAL LIBRARY
MONTEREY, CA 93940